

# A Loop-philic Pseudoscalar

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We construct a weakly-coupled renormalizable model to explain the 750 GeV diphoton excess. The 750 GeV resonance (denoted as  $X(750)$ ) is interpreted as a pseudoscalar coming from a complex singlet. The model also naturally provides a dark matter candidate. One most attractive feature of the model is that decays of  $X(750)$  are all loop-induced so the diphoton rate is not diluted by unwanted tree level branching fractions. Relevant Yukawa interactions need not to be tuned to near non-perturbative region to explain the rate. The model is highly predictive, including the pseudoscalar nature of  $X(750)$ , and two nearly mass-degenerate exotic quarks carrying electric charge  $5/3$  and  $2/3$ , respectively. Rich phenomenology is expected with respect to collider searches, flavor physics and dark matter detection, if  $X(750)$  can be pinned down by future LHC experiments.

## I. INTRODUCTION

The discovery of the 125 GeV Higgs boson [1, 2] and the non-discovery of any new physics signature at the LHC Run I mark an amazing triumph of the standard model (SM) and have significant implications for beyond the SM (BSM) physics searches. Now the guidelines on BSM searches heavily rely on either highly-debated theoretical issues (*e.g.* Higgs mass fine-tuning), or observational clues (*e.g.* dark matter (DM)) which however need not be related to energy scales accessible at present or foreseeable accelerators. Therefore it is very fortunate if the already obtained LHC Run II data can reveal some new phenomena which will in turn fast track our BSM searches and understanding of those fundamental theoretical and observational questions. Recently the ATLAS and CMS collaborations have reported an excess of diphoton events around 750 GeV invariant mass with a local significance of  $3.6\sigma$  and  $2.6\sigma$ , respectively, using the 13 TeV LHC data [3, 4]. If this is not merely due to statistical fluctuations or some unknown systematic uncertainties, the excess will definitely have far-reaching consequences for any BSM theory and profoundly shape our understanding of elementary particles and the universe. At present no definite conclusion can be drawn with regard to the very existence of the resonance, and more data and refined photon energy calibration are warranted to arrive at a final confirmation or exclusion. It is nevertheless tempting for theorists to dig out the agents behind the scene which contribute to such a surprising phenomenon, assuming the existence of the

750 GeV resonance (denoted as  $X(750)$ ). Therefore, the excess triggered a huge amount of theoretical and phenomenological investigations [5–102]. The excess is to some extent surprising because it is somewhat challenging to interpret it naturally in a weakly-coupled model. Taking into account 8 TeV results [103–106], the production mechanism of  $X(750)$  is very likely to be gluon fusion, based on parton luminosity considerations [11]. Here we only consider the case that the diphoton excess indeed corresponds to a new resonance  $X(750)$  which is produced in gluon fusion and subsequently decays to exactly two photons. We note that there are many other interesting possibilities of exotic kinematics [10] which we won't pursue in the following. The Landau-Yang theorem [107, 108] and the pursuit of a renormalizable theory prompt us to consider the possibility that  $X(750)$  is spin-zero and both  $gg \rightarrow X(750)$  and  $X(750) \rightarrow \gamma\gamma$  proceed via loops. It has been shown [10] that in this case particles beyond the SM have to be introduced in the loops so as to provide a sufficient diphoton rate and at the same time to make the theory compatible with collider constraints from other channels. Even with this addition, generically it is still difficult to produce the diphoton cross section required to explain the experimental results (about 5 fb is needed [10, 11]) naturally in renormalizable models. Relevant Yukawa interactions are often tuned to near non-perturbative region (or a large number of new particles are introduced), and ad hoc assumptions are often made (explicitly or implicitly) to suppress the tree level decay of  $X(750)$  to SM particles. Aimed at tackling these difficulties, in this Letter we propose a simple, weakly-coupled extension of the SM to explain the diphoton excess. The model is fully gauge invariant under SM gauge groups and completely renormalizable. One very attractive feature of the model is that decays of  $X(750)$  are always loop-induced, in this way the early appearance of the diphoton excess is naturally explained. In the next section we present the contents of the model and discuss its important phenomenological aspects. Finally we present our discussion and conclusion.

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Field	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$Z_2$
$\mathbb{S}$	0	<b>1</b>	<b>1</b>	0	even
$\Phi$	0	<b>1</b>	<b>2</b>	1/2	odd
$Q_L$	1/2	<b>3</b>	<b>2</b>	7/6	odd
$Q_R$	1/2	<b>3</b>	<b>2</b>	7/6	odd

TABLE I: Field contents in addition to SM in our model.  $\mathbb{S}$  is complex.

## II. THE MODEL

We introduce a complex singlet scalar  $\mathbb{S}$ , an inert doublet scalar  $\Phi$  and an inert vector-like doublet quark  $Q$ , in addition to SM fields. The complete list of relevant representations and quantum numbers are listed in Table I. CP conservation is required in the extended sector, for both the Lagrangian and the vacuum. We call  $\Phi$  and  $Q$  inert because they are odd under a  $Z_2$  symmetry, i.e.  $\Phi \rightarrow -\Phi, Q \rightarrow -Q$  while SM fields and  $\mathbb{S}$  are even. We identify the particle corresponding to the CP-odd component of  $\mathbb{S}$  as the  $X(750)$ . In this construction the particle participating in  $gg \rightarrow X(750)$  and  $X(750) \rightarrow \gamma\gamma$  triangle loops is the inert vector-like quark  $Q = \begin{pmatrix} Q_{5/3} \\ Q_{2/3} \end{pmatrix}$ , where the subscripts label the electric charge of the weak isospin components. The role of vector-like quarks in (extra) Higgs boson production and decay has been extensively studied, *e.g.* [109–113]. Here the representations of vector-like quarks are chosen carefully so as to produce a large diphoton rate more easily. The particular, simple representation of  $Q$  listed in Table I was noticed by [10, 53] and found to generate relatively large diphoton rate, due to the large multiplicity and electric charge involved. We note that when making the above statement there is a crucial idealized assumption, *i.e.* only the di-gluon decay channel dominates the total width of  $X(750)$ . If  $X(750)$  is a CP-even scalar, its tree level decays to  $W, Z, h, t$  ( $h$  denotes the 125 GeV Higgs boson) are in general open, albeit they might be suppressed by mixing angles in certain model construction cases. A CP-odd scalar is more desirable because it has no tree level trilinear coupling to  $WW, ZZ, hh$  (also its loop function has larger asymptotic value). This allures us to also forbid its tree level coupling to SM fermions (and to  $Zh$ ), which is not possible in a usual two-Higgs-doublet model setup. This impossibility arises from the particular representation assignment of the extra Higgs field, which can otherwise be dissolved by demanding the CP-odd scalar come from a complex singlet, which is just the  $\mathbb{S}$  introduced in our model. In this way the di-gluon channel can naturally dominate the total width of  $X(750)$ , without being diluted by unwanted tree level decays. The introduction of  $\Phi$  and making  $\Phi$  and  $Q$  inert is crucial as well. This becomes evident when we consider the decay of  $Q$ . On one hand, we would like  $Q$  to

decay in some manner because stable colored and charged particles are stringently constrained [114]. On the other hand, if  $Q$  is allowed to decay via mixing with SM quarks as was considered in [10, 53], the same mixing effect will reintroduce tree level couplings of  $X(750)$  to SM fermions and thus spoil our original goal. Inspired by flavored DM constructions [32, 115, 116], we are led to make  $Q$  decay to final states involving DM and thus  $\Phi$  and the  $Z_2$  assignments are introduced. The lightest particle from the  $Z_2$ -odd sector, if color and electrically neutral, becomes a DM candidate, which is taken to be the CP-even or CP-odd neutral particle from  $\Phi$ . It is interesting to note that if the DM particle is heavier than half of the mass of  $X(750)$  (which will be assumed in the following), then  $X(750)$  will not have any tree level decay (even 3-body and multi-body tree level decays are forbidden as well). In such a case  $X(750)$  is therefore called *loop-philic*. In general, loop-induced decay of  $X(750)$  to di-gluon will dominate the width. Minor contributions of  $\gamma\gamma, WW, \gamma Z, ZZ, hh, Zh, tt$  decay modes and decays to final states involving the additional CP-even  $Z_2$ -even Higgs boson  $h'$  are also expected, all of which still have to proceed via loops. The diphoton branching ratio is not diluted by unwanted tree level branching fractions, which is a very attractive feature of the model.

With all ingredients at our hand, we can now write down the most general CP-conserving renormalizable gauge-invariant Lagrangian containing the introduced fields satisfying symmetry assignments dictated by Table I ( $H$  denotes the original Higgs doublet introduced in the SM)

$$\mathcal{L} = \mathcal{L}_{H\mathbb{S}\Phi} + \mathcal{L}_{QMass} + \mathcal{L}_{QGauge} + \mathcal{L}_{QS} + \mathcal{L}_{Q\Phi}, \quad (1)$$

$$\begin{aligned} \mathcal{L}_{H\mathbb{S}\Phi} &= (D^\mu H)^\dagger (D_\mu H) + (\partial^\mu \mathbb{S})^\dagger (\partial_\mu \mathbb{S}) \\ &+ (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(H, \mathbb{S}, \Phi), \end{aligned} \quad (2)$$

$$\mathcal{L}_{QMass} = -M \bar{Q}_L Q_R + \text{h.c.}, \quad (3)$$

$$\mathcal{L}_{QGauge} = \bar{Q}_L \not{D} Q_L + \bar{Q}_R \not{D} Q_R, \quad (4)$$

$$\mathcal{L}_{QS} = -\lambda_{QS1} \mathbb{S} \bar{Q}_L Q_R - \lambda_{QS2} \mathbb{S}^\dagger \bar{Q}_L Q_R + \text{h.c.}, \quad (5)$$

$$\mathcal{L}_{Q\Phi} = -\lambda_{Q\Phi i} \bar{Q}_L \cdot \Phi u_{Ri} + \text{h.c.} \quad (6)$$

In Eq. (6)  $u_{Ri}, i = 1, 2, 3$  denotes the three generations of SM up type quarks and  $i$  is summed over. Covariant derivatives in the above equations are understood to be consistent with the representations and quantum numbers listed in Table I. For completeness, we also explicitly write down the scalar potential  $V(H, \mathbb{S}, \Phi)$  introduced in Eq. (2)

$$\begin{aligned} V(H, \mathbb{S}, \Phi) &= \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_{S1}^3 \mathbb{S} \\ &+ \mu_{S2}^2 \mathbb{S}^2 + \mu_{S3}^2 \mathbb{S}^\dagger \mathbb{S} + \mu_{S4} \mathbb{S}^3 + \mu_{S5} (\mathbb{S}^\dagger \mathbb{S}) \mathbb{S} + \lambda_{S1} \mathbb{S}^4 \\ &+ \lambda_{S2} (\mathbb{S}^\dagger \mathbb{S}) \mathbb{S}^2 + \lambda_{S3} (\mathbb{S}^\dagger \mathbb{S})^2 + \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 \\ &+ \mu_{HS} (H^\dagger H) \mathbb{S} + \lambda_{HS1} (H^\dagger H) \mathbb{S}^2 \\ &+ \lambda_{HS2} (H^\dagger H) (\mathbb{S}^\dagger \mathbb{S}) + \lambda_{H\Phi1} (H^\dagger H) (\Phi^\dagger \Phi) \\ &+ \lambda_{H\Phi2} (H^\dagger \Phi) (\Phi^\dagger H) + \lambda_{H\Phi3} (H^\dagger \Phi)^2 \\ &+ \mu_{S\Phi} \mathbb{S} (\Phi^\dagger \Phi) + \lambda_{S\Phi1} \mathbb{S}^2 (\Phi^\dagger \Phi) + \lambda_{S\Phi2} (\mathbb{S}^\dagger \mathbb{S}) (\Phi^\dagger \Phi) \\ &+ \text{h.c.}, \end{aligned} \quad (7)$$

In Eq. (7) h.c. in the last line represents the hermitian conjugate of the terms which are present in the potential but are not self-conjugate. We require all  $\mu's, \lambda's$  to be real so as to make the Lagrangian CP-invariant ( $M$  can always be made real by rephasing  $Q_L, Q_R$  fields). We assume  $Z_2$  is also preserved by vacuum and thus  $\langle \Phi \rangle = 0$ . It is legitimate to shift  $\mathbb{S}$  in order to make  $\langle \mathbb{S} \rangle = 0$ , which will be assumed in the following. This offers the convenience that the tree level mass of  $Q$  is just  $M$ . The mass degeneracy of  $Q_{5/3}$  and  $Q_{2/3}$  is broken only by loop effects by which gauge boson loops will make  $Q_{5/3}$  slightly heavier than  $Q_{2/3}$ . We do not expect loops induced by  $\mathcal{L}_{Q\Phi}$  to substantially enlarge this mass difference. Therefore in the following calculation we simply take  $Q_{5/3}$  and  $Q_{2/3}$  to be mass-degenerate at  $M$ .

For notational convenience, we write  $\mathbb{S} = \frac{1}{\sqrt{2}}(S + iA)$  in which the particle excitation of  $A$  is just  $X(750)$ , with mass  $m_A = 750$  GeV. To discuss the diphoton rate of  $A$ , the most important part of the Lagrangian is  $\mathcal{L}_{QS}$ , which gives the following effective Lagrangian

$$\mathcal{L}_{AQQ} = -y(\bar{Q}_{5/3}i\gamma^5 Q_{5/3} + \bar{Q}_{2/3}i\gamma^5 Q_{2/3})A, \quad (8)$$

where we introduced the effective Yukawa coupling constant for  $AQQ$  interaction  $y \equiv \frac{\lambda_{QS1} - \lambda_{QS2}}{\sqrt{2}}$ . We also introduce an effective Yukawa coupling constant  $y'$  for  $h'QQ$  interaction  $y' \equiv \frac{\lambda_{QS1} + \lambda_{QS2}}{\sqrt{2}}$ . Assuming  $x \equiv \frac{m_A^2}{4M^2} < 1$ , the leading order partial widths of  $A \rightarrow gg, \gamma\gamma$  are calculated as [117, 118]

$$\Gamma(A \rightarrow gg) = \frac{\alpha_s^2 m_A^3 y^2}{8\pi^3 M^2} \left( \frac{\arcsin^2 \sqrt{x}}{x} \right)^2, \quad (9)$$

$$\Gamma(A \rightarrow \gamma\gamma) = \frac{841\alpha_{em}^2 m_A^3 y^2}{576\pi^3 M^2} \left( \frac{\arcsin^2 \sqrt{x}}{x} \right)^2, \quad (10)$$

For a loop-philic  $A$ , other important decay channels considered here include  $WW, ZZ, \gamma Z$ , with approximate partial width ratios calculated to be  $\frac{\Gamma(A \rightarrow WW)}{\Gamma(A \rightarrow \gamma\gamma)} = 0.91$ ,  $\frac{\Gamma(A \rightarrow ZZ)}{\Gamma(A \rightarrow \gamma\gamma)} = 0.60$ ,  $\frac{\Gamma(A \rightarrow \gamma Z)}{\Gamma(A \rightarrow \gamma\gamma)} = 0.06$ . Loop-induced decays to  $tt, cc, uu, tc, tu, cu$  and  $hh, h'h', hh', Zh, Zh'$  are expected to be small if we require  $\lambda_{Q\Phi i}, y'$  and the mixing in the CP-even Higgs sector to be small. Therefore for total width calculation, we only take into account  $A \rightarrow gg, \gamma\gamma, WW, ZZ, \gamma Z$ . All relevant K-factors are taken to be 1, especially because it is expected that for  $gg$  initial and final states, the K-factor effect cancels a lot when calculating the rate. MSTW2008 PDF [119] is used for parton-parton luminosity calculations. In FIG. 1 we color the parameter region where the diphoton  $\sigma \times \text{Br}$  can reach 4, 8, 12, 20 fb. We note that for the heavy DM case ( $\gtrsim 550$  GeV) (which is one option favored by relic density considerations, see the paragraph on DM below), essentially there is no lower bound on the mass of  $Q_{2/3}$  other than the DM mass assuming 100%

decay to top final states [32].<sup>1</sup> Therefore for a wide range of  $M$ , there exists a fully perturbative region of  $y$  to realize the observed diphoton rate. If we take a benchmark point  $M = 1$  TeV,  $y = 1.0$ , we will get  $\sigma(gg \rightarrow A \rightarrow \gamma\gamma) = 6.4$  fb, which just falls in the right range needed to explain the excess. The total width of  $A$  at this benchmark point is about 18 MeV which is not able to also account for the apparently large width hinted by ATLAS [3]. However the hint is quite preliminary and not supported by CMS [4] so we still stick to the narrow width interpretation. With the above-mentioned partial width ratios, it is easy to check that for  $X(750)$  no bounds are relevant at present with regard to LHC searches in dijet,  $WW, ZZ, \gamma Z$  channels [124–130], which in turn provides a natural reason why the diphoton channel popped up first. We have checked that the modification of the  $gg \rightarrow h \rightarrow \gamma\gamma$  signal strength due to  $Q$  is safely negligible. The contribution of  $Q_{5/3}$  and  $Q_{2/3}$  to electroweak precision observables is also negligible due to their vector-like nature and approximate mass-degeneracy [131].

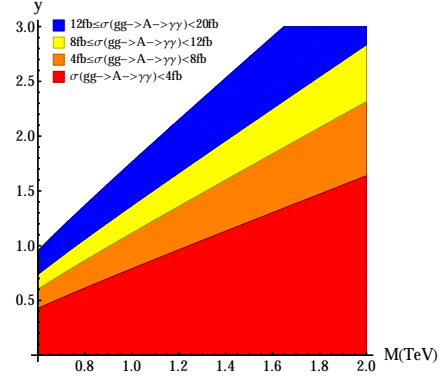


FIG. 1: Diphoton rate in our model plotted in the  $M - y$  plane. The color scheme is described in the plot.

A few remarks are in order here with respect to DM phenomenology in the model. In fact, the model possesses a decoupling limit in which makes DM phenomenology here approach the usual inert doublet model (IDM) [132]. There are three additional factors contributing to DM phenomenology compared with IDM. The first is the mixing of two CP-even neutral Higgs bosons in the  $Z_2$ -even sector. The second is additional trilinear and quartic couplings in the scalar sector. The third is the new  $\mathcal{L}_{Q\Phi}$  interactions. The impact of all three factors can be made small by keeping relevant mixing and coupling small and thus the model approaches the IDM

<sup>1</sup> There are collider searches for top-quark partners with 5/3 electric charge [120–123]. However their bounds cannot be directly applied to our case because some different kinematic features (e.g.  $H_T$  distribution) are involved.

limit. It is known that the IDM has a region of parameter space corresponding to large DM mass ( $\gtrsim 550$  GeV) which can give correct relic density and satisfy direct detection bound [133]. Thus our model is expected to be able to produce correct DM relic density and be safe from direct detection constraints. We note that it is interesting, though beyond the scope of this Letter, to consider the case in which one or more of these three factors make a sizable contribution to DM annihilation or direct detection and thus have interplay with ordinary IDM.

Our model can be tested in the future in various manners besides the diphoton and diboson rates. First, our model predicts a CP-odd scalar whose CP-property can be tested via investigating the final state differential distribution of  $gg \rightarrow A \rightarrow WW, ZZ, \gamma Z$ . Second, our model predicts an additional CP-even scalar  $h'$  which can mix with the 125 GeV Higgs boson. Its trail can be detected in future precision electroweak or Higgs studies. This additional CP-even scalar can also be produced directly at colliders and decay to SM final states. Inert vector-like quarks might contribute in its production and decay loop, however the associated rate is not linked tightly to  $X(750)$  production because in our construction  $y'$  can be adjusted independently with respect to  $y$ . Third, exotic quarks of electric charge  $5/3$  and  $2/3$  are expected and nearly mass-degenerate, which can be searched for at future hadron or linear colliders, via signatures such as lepton(s) + jets +  $\cancel{E}_T$  (leptons and jets come from  $t, W, Z$  from  $Q_{5/3}, Q_{2/3}$  decay and can often be soft). The chirality structure of  $\mathcal{L}_{Q\Phi}$  can be further studied via studying the polarization of the top quark in the process, *e.g.* in the same spirit as [134].  $\mathcal{L}_{Q\Phi}$  also contributes to flavor observable such as  $\Delta m_D$ , which at present provides the constraint  $|\lambda_{Q\Phi u} \lambda_{Q\Phi c}| \lesssim 5 \times 10^{-3}$ . More parameter space on these two couplings is expected to be probed by future improved flavor experiments and refined lattice calculations. Furthermore, scalars from the inert doublet in our model can be probed by future dark matter experiments and production at very high energy hadron, lepton, and lepton-hadron colliders.

### III. DISCUSSION AND CONCLUSION

In this Letter we introduced a weakly-coupled renormalizable model in which there exists a particle whose tree level decays are all forbidden and therefore can only decay via quantum effects. This particle is a pseudoscalar coming from a complex singlet scalar field.

With appropriate vector-like fermions conspiring in the loop it is easy to produce a sufficiently large diphoton rate for  $X(750)$  without driving relevant Yukawa couplings to non-perturbative region. Interestingly enough, the prohibition of tree level decays of  $X(750)$  naturally leads to a dark matter candidate in the model. If  $X(750)$  can be confirmed in the future, there should be rich phenomenology with respect to collider searches, flavor physics and dark matter detection. We note that this loop-philic construction is not specific to the  $(\mathbf{3}, \mathbf{2}, 7/6)$  representation and quantum number chosen for  $Q$ . Other representations and quantum numbers (such as those considered in [10]) can be easily accommodated as long as appropriate representations for inert scalars are chosen, although one might be confronted with different (perhaps more stringent) theoretical and phenomenological constraints in such cases.

The 750 GeV diphoton excess is a huge surprise to the high energy physics community. On one hand, physics beyond the SM has been sought for for a long time at colliders without success. The diphoton excess, though preliminary, has an unexpected possibility to become the first smoking gun signature of physics beyond the SM at the LHC, and thus clearly warrants further experimental and theoretical investigations. On the other hand, there have been two major trends in new physics model building, *i.e.* weak dynamics (*e.g.* supersymmetry) and strong dynamics (*e.g.* composite Higgs). Weak dynamics has some special advantages such as its renormalizability and being easier to make predictions. However the diphoton excess, at first glance, is difficult to explain naturally in a completely weakly-coupled theory. Our study shows that with appropriate model construction it is possible to naturally accommodate the diphoton excess with the addition of only a few particles in a completely weakly-coupled renormalizable gauge-invariant framework. In this Letter a minimal realization of such a framework is presented, in which the diphoton excess appears the earliest is fully expected due to the loop-philic nature of  $X(750)$ .

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- [1] ATLAS, G. Aad *et al.*, Phys. Lett. **B716**, 1 (2012), 1207.7214.
  - [2] CMS, S. Chatrchyan *et al.*, Phys. Lett. **B716**, 30 (2012), 1207.7235.
  - [3] ATLAS, (2015), ATLAS-CONF-2015-081.

- [4] CMS, (2015), CMS-PAS-EXO-15-004.
- [5] K. Harigaya and Y. Nomura, (2015), 1512.04850.
- [6] Y. Mambrini, G. Arcadi, and A. Djouadi, (2015), 1512.04913.
- [7] M. Backovic, A. Mariotti, and D. Redigolo, (2015),

- 1512.04917.
- [8] A. Angelescu, A. Djouadi, and G. Moreau, (2015), 1512.04921.
  - [9] Y. Nakai, R. Sato, and K. Tobioka, (2015), 1512.04924.
  - [10] S. Knapen, T. Melia, M. Papucci, and K. Zurek, (2015), 1512.04928.
  - [11] D. Buttazzo, A. Greljo, and D. Marzocca, (2015), 1512.04929.
  - [12] A. Pilaftsis, (2015), 1512.04931.
  - [13] R. Franceschini *et al.*, (2015), 1512.04933.
  - [14] S. Di Chiara, L. Marzola, and M. Raidal, (2015), 1512.04939.
  - [15] T. Higaki, K. S. Jeong, N. Kitajima, and F. Takahashi, (2015), 1512.05295.
  - [16] S. D. McDermott, P. Meade, and H. Ramani, (2015), 1512.05326.
  - [17] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz, and T. You, (2015), 1512.05327.
  - [18] M. Low, A. Tesi, and L.-T. Wang, (2015), 1512.05328.
  - [19] B. Bellazzini, R. Franceschini, F. Sala, and J. Serra, (2015), 1512.05330.
  - [20] R. S. Gupta, S. Jager, Y. Kats, G. Perez, and E. Stamou, (2015), 1512.05332.
  - [21] C. Petersson and R. Torre, (2015), 1512.05333.
  - [22] E. Molinaro, F. Sannino, and N. Vignaroli, (2015), 1512.05334.
  - [23] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, and T. Li, (2015), 1512.05439.
  - [24] Q.-H. Cao, Y. Liu, K.-P. Xie, B. Yan, and D.-M. Zhang, (2015), 1512.05542.
  - [25] S. Matsuzaki and K. Yamawaki, (2015), 1512.05564.
  - [26] A. Kobakhidze, F. Wang, L. Wu, J. M. Yang, and M. Zhang, (2015), 1512.05585.
  - [27] R. Martinez, F. Ochoa, and C. F. Sierra, (2015), 1512.05617.
  - [28] P. Cox, A. D. Medina, T. S. Ray, and A. Spray, (2015), 1512.05618.
  - [29] D. Becirevic, E. Bertuzzo, O. Sumensari, and R. Z. Funchal, (2015), 1512.05623.
  - [30] J. M. No, V. Sanz, and J. Setford, (2015), 1512.05700.
  - [31] S. V. Demidov and D. S. Gorbunov, (2015), 1512.05723.
  - [32] W. Chao, R. Huo, and J.-H. Yu, (2015), 1512.05738.
  - [33] S. Fichet, G. von Gersdorff, and C. Royon, (2015), 1512.05751.
  - [34] D. Curtin and C. B. Verhaaren, (2015), 1512.05753.
  - [35] L. Bian, N. Chen, D. Liu, and J. Shu, (2015), 1512.05759.
  - [36] J. Chakraborty, A. Choudhury, P. Ghosh, S. Mondal, and T. Srivastava, (2015), 1512.05767.
  - [37] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion, and Y. Jiang, (2015), 1512.05771.
  - [38] P. Agrawal, J. Fan, B. Heidenreich, M. Reece, and M. Strassler, (2015), 1512.05775.
  - [39] C. Csaki, J. Hubisz, and J. Terning, (2015), 1512.05776.
  - [40] A. Falkowski, O. Slone, and T. Volansky, (2015), 1512.05777.
  - [41] D. Aloni, K. Blum, A. Dery, A. Efrati, and Y. Nir, (2015), 1512.05778.
  - [42] Y. Bai, J. Berger, and R. Lu, (2015), 1512.05779.
  - [43] E. Gabrielli *et al.*, (2015), 1512.05961.
  - [44] R. Benbrik, C.-H. Chen, and T. Nomura, (2015), 1512.06028.
  - [45] J. S. Kim, J. Reuter, K. Rolbiecki, and R. R. de Austri, (2015), 1512.06083.
  - [46] A. Alves, A. G. Dias, and K. Sinha, (2015), 1512.06091.
  - [47] E. Megias, O. Pujolas, and M. Quiros, (2015), 1512.06106.
  - [48] L. M. Carpenter, R. Colburn, and J. Goodman, (2015), 1512.06107.
  - [49] J. Bernon and C. Smith, (2015), 1512.06113.
  - [50] W. Chao, (2015), 1512.06297.
  - [51] M. T. Arun and P. Saha, (2015), 1512.06335.
  - [52] C. Han, H. M. Lee, M. Park, and V. Sanz, (2015), 1512.06376.
  - [53] S. Chang, (2015), 1512.06426.
  - [54] I. Chakraborty and A. Kundu, (2015), 1512.06508.
  - [55] R. Ding, L. Huang, T. Li, and B. Zhu, (2015), 1512.06560.
  - [56] H. Han, S. Wang, and S. Zheng, (2015), 1512.06562.
  - [57] X.-F. Han and L. Wang, (2015), 1512.06587.
  - [58] M.-x. Luo, K. Wang, T. Xu, L. Zhang, and G. Zhu, (2015), 1512.06670.
  - [59] J. Chang, K. Cheung, and C.-T. Lu, (2015), 1512.06671.
  - [60] D. Bardhan *et al.*, (2015), 1512.06674.
  - [61] T.-F. Feng, X.-Q. Li, H.-B. Zhang, and S.-M. Zhao, (2015), 1512.06696.
  - [62] O. Antipin, M. Mojaza, and F. Sannino, (2015), 1512.06708.
  - [63] F. Wang, L. Wu, J. M. Yang, and M. Zhang, (2015), 1512.06715.
  - [64] J. Cao *et al.*, (2015), 1512.06728.
  - [65] F. P. Huang, C. S. Li, Z. L. Liu, and Y. Wang, (2015), 1512.06732.
  - [66] W. Liao and H.-q. Zheng, (2015), 1512.06741.
  - [67] J. J. Heckman, (2015), 1512.06773.
  - [68] M. Dhuria and G. Goswami, (2015), 1512.06782.
  - [69] X.-J. Bi, Q.-F. Xiang, P.-F. Yin, and Z.-H. Yu, (2015), 1512.06787.
  - [70] J. S. Kim, K. Rolbiecki, and R. R. de Austri, (2015), 1512.06797.
  - [71] L. Berthier, J. M. Cline, W. Shepherd, and M. Trott, (2015), 1512.06799.
  - [72] W. S. Cho *et al.*, (2015), 1512.06824.
  - [73] J. M. Cline and Z. Liu, (2015), 1512.06827.
  - [74] M. Bauer and M. Neubert, (2015), 1512.06828.
  - [75] M. Chala, M. Duerr, F. Kahlhoefer, and K. Schmidt-Hoberg, (2015), 1512.06833.
  - [76] D. Barducci, A. Goudelis, S. Kulkarni, and D. Sengupta, (2015), 1512.06842.
  - [77] S. M. Boucenna, S. Morisi, and A. Vicente, (2015), 1512.06878.
  - [78] C. W. Murphy, (2015), 1512.06976.
  - [79] A. E. C. Hernandez and I. Nisandzic, (2015), 1512.07165.
  - [80] U. K. Dey, S. Mohanty, and G. Tomar, (2015), 1512.07212.
  - [81] G. M. Pelaggi, A. Strumia, and E. Vigiani, (2015), 1512.07225.
  - [82] J. de Blas, J. Santiago, and R. Vega-Morales, (2015), 1512.07229.
  - [83] A. Belyaev *et al.*, (2015), 1512.07242.
  - [84] P. S. B. Dev and D. Teresi, (2015), 1512.07243.
  - [85] W.-C. Huang, Y.-L. S. Tsai, and T.-C. Yuan, (2015), 1512.07268.
  - [86] S. Moretti and K. Yagyu, (2015), 1512.07462.
  - [87] K. M. Patel and P. Sharma, (2015), 1512.07468.
  - [88] M. Badziak, (2015), 1512.07497.
  - [89] S. Chakraborty, A. Chakraborty, and S. Raychaudhuri,

- (2015), 1512.07527.
- [90] Q.-H. Cao, S.-L. Chen, and P.-H. Gu, (2015), 1512.07541.
  - [91] W. Altmannshofer *et al.*, (2015), 1512.07616.
  - [92] M. Cvetič, J. Halverson, and P. Langacker, (2015), 1512.07622.
  - [93] J. Gu and Z. Liu, (2015), 1512.07624.
  - [94] B. C. Allanach, P. S. B. Dev, S. A. Renner, and K. Sakurai, (2015), 1512.07645.
  - [95] H. Davoudiasl and C. Zhang, (2015), 1512.07672.
  - [96] N. Craig, P. Draper, C. Kilic, and S. Thomas, (2015), 1512.07733.
  - [97] K. Das and S. K. Rai, (2015), 1512.07789.
  - [98] K. Cheung, P. Ko, J. S. Lee, J. Park, and P.-Y. Tseng, (2015), 1512.07853.
  - [99] J. Liu, X.-P. Wang, and W. Xue, (2015), 1512.07885.
  - [100] J. Zhang and S. Zhou, (2015), 1512.07889.
  - [101] J. A. Casas, J. R. Espinosa, and J. M. Moreno, (2015), 1512.07895.
  - [102] L. J. Hall, K. Harigaya, and Y. Nomura, (2015), 1512.07904.
  - [103] ATLAS, G. Aad *et al.*, Phys. Rev. Lett. **113**, 171801 (2014), 1407.6583.
  - [104] ATLAS, G. Aad *et al.*, Phys. Rev. **D92**, 032004 (2015), 1504.05511.
  - [105] CMS, V. Khachatryan *et al.*, Phys. Lett. **B750**, 494 (2015), 1506.02301.
  - [106] CMS, (2015), CMS-PAS-EXO-12-045.
  - [107] L. D. Landau, Dokl. Akad. Nauk Ser. Fiz. **60**, 207 (1948).
  - [108] C.-N. Yang, Phys. Rev. **77**, 242 (1950).
  - [109] N. Bonne and G. Moreau, Phys. Lett. **B717**, 409 (2012), 1206.3360.
  - [110] G. Moreau, Phys. Rev. **D87**, 015027 (2013), 1210.3977.
  - [111] S. A. R. Ellis, R. M. Godbole, S. Gopalakrishna, and J. D. Wells, JHEP **09**, 130 (2014), 1404.4398.
  - [112] A. Angelescu, A. Djouadi, and G. Moreau, (2015), 1510.07527.
  - [113] A. Alves, D. A. Camargo, and A. G. Dias, (2015), 1511.04449.
  - [114] Particle Data Group, K. A. Olive *et al.*, Chin. Phys. **C38**, 090001 (2014).
  - [115] P. Agrawal, S. Blanchet, Z. Chacko, and C. Kilic, Phys. Rev. **D86**, 055002 (2012), 1109.3516.
  - [116] C. Kilic, M. D. Klimek, and J.-H. Yu, Phys. Rev. **D91**, 054036 (2015), 1501.02202.
  - [117] A. Djouadi, Phys. Rept. **457**, 1 (2008), hep-ph/0503172.
  - [118] A. Djouadi, Phys. Rept. **459**, 1 (2008), hep-ph/0503173.
  - [119] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. **C63**, 189 (2009), 0901.0002.
  - [120] CMS, S. Chatrchyan *et al.*, Phys. Rev. Lett. **112**, 171801 (2014), 1312.2391.
  - [121] ATLAS, G. Aad *et al.*, Phys. Rev. **D91**, 112011 (2015), 1503.05425.
  - [122] ATLAS, G. Aad *et al.*, JHEP **10**, 150 (2015), 1504.04605.
  - [123] CMS, (2015), CMS-PAS-B2G-15-006.
  - [124] CMS, (2015), CMS-PAS-EXO-14-005.
  - [125] CMS, (2015), CMS-PAS-HIG-14-008.
  - [126] ATLAS, G. Aad *et al.*, (2015), 1509.00389.
  - [127] CMS, (2013), CMS-PAS-HIG-13-014.
  - [128] ATLAS, G. Aad *et al.*, (2015), 1507.05930.
  - [129] CMS, (2015), CMS-PAS-HIG-14-007.
  - [130] ATLAS, G. Aad *et al.*, Phys. Lett. **B738**, 428 (2014), 1407.8150.
  - [131] H.-J. He, N. Polonsky, and S.-f. Su, Phys. Rev. **D64**, 053004 (2001), hep-ph/0102144.
  - [132] N. G. Deshpande and E. Ma, Phys. Rev. **D18**, 2574 (1978).
  - [133] M. Krawczyk, N. Darvishi, and D. Sokolowska, The Inert Doublet Model and its extensions, 2015, 1512.06437.
  - [134] E. L. Berger, Q.-H. Cao, J.-H. Yu, and H. Zhang, Phys. Rev. Lett. **109**, 152004 (2012), 1207.1101.